Synergy of Particle Swarm Optimization and Bacterial Foraging for SSSC Damping Controller Design

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Abstract

Social foraging behaviour of *Escherichia coli* bacteria has recently been explored to develop a novel algorithm for optimization and control. One of the major driving forces of Bacterial Foraging Optimization Algorithm (BFOA) is the chemotactic movement of a virtual bacterium that models a trial solution of the optimization problem. However, during the process of chemotaxis, the BFOA depends on random search directions which may lead to delay in reaching the global solution. This paper comes up with a hybrid approach involving Particle Swarm Optimization (PSO) and BFOA algorithm called Bacterial Swarm Optimization (BSO) for designing Static Synchronous Series Compensator (SSSC) in a power system. In BSO, the search directions of tumble behaviour for each bacterium are oriented by the individual's best location and the global best location of PSO. The proposed hybrid algorithm has been extensively compared with BFOA and PSO. Simulation results have shown the validity of the proposed BSO in tuning SSSC compared with BFOA and PSO. Moreover, the results are presented to demonstrate the effectiveness of the proposed controller to improve the power system stability over a wide range of loading conditions.

Keywords

SSSC; Particle Swarm Optimization; Bacterial Foraging; Hybrid Algorithm; Damping Oscillations

Introduction

The power transfer in an integrated power system is constrained by transient stability, voltage stability and small signal stability. These constraints limit a full utilization of available transmission corridors. Flexible AC Transmission System (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability limit and thermal limit (Kundur, 1994).

Recently, there has been a surge of interest in the development and use of FACTS controllers in power transmission systems (Lee, and Sun, 2002; Sen, 1998; Ngamroo, 2001; Ngamroo, and Kongprawechnon, 2003; Zhang, 2003). These controllers utilize power electronics devices to provide more flexibility to AC power systems. The theory and the modeling technique of SSSC device using an Electromagnetic Transients Program (EMTP) simulation package is presented in (Sen, 1998). SSSC is designed in (Ngamroo, 2001) to stabilize the frequency of oscillation in an interconnected power system. This SSSC located in series with the tie line between any interconnected areas, is applicable to stabilize the area frequency of oscillations by high speed control of tie line power through the interconnections. A robust design of the lead/lag controller equipped with the SSSC for stabilization of frequency oscillations is discussed in (Kongprawechnon, 2003). A multi control functional model of SSSC for power system analysis is described in (Zhang, 2003). This model can be used for steady state control of one of the following parameters: 1) the active power flow on the transmission line; 2) the reactive power flow on the transmission line; 3) the voltage at the bus; 4) the impedance (precisely reactance) of the transmission line. A robust damping controller based on Fuzzy Logic Controller (FLC) is introduced in (Chen, Lie, and Vilathgamuwa, 2004). The only input signal for this damping controller is the real power measurement at the location of the SSSC to generate the modulation index for controlling the injected voltage of the Voltage Source Converter (VSC) while its phase angle is required to remain constant with respect to local reference voltage vector. A new Genetic Algorithm (GA) based approach for optimal selection of the SSSC damping controller parameters in order to shift the closed loop eigenvalues toward the desired stability region is designed in (Kazemi, Ladjevardi, and Masoum, 2005). The dynamic operation of both Static Synchronous Compensator (STATCOM) and SSSC based on a new model comprising full 48-pulse Gate Turn Off (GTO) VSC is investigated in (El-Moursi, and Sharaf, 2006). These models combined reactive power compensation and voltage stabilization of the electric grid network. The rate of dissipation of transient energy is used as a

measure of system damping in (Haque, 2006). This concept is applied to determine the additional damping provided by a STATCOM and SSSC. GA optimization technique to design FACTS based damping controllers for Single Machine Infinite Bus (SMIB) is applied in (Panda, and Padhy, 2007). The analytical expressions for this additional damping are derived and compared for classical model of a simple power system. The influence of SSSC and STATCOM on the synchronizing power and damping power of a SMIB is introduced in (Jowder, 2007). The impacts of different SSSC control modes on a small signal and transient stability of a power system is discussed in (Castro, Ayres, Da-Costa, and Da-Silva, 2007). The application of a SSSC controller to improve the transient stability performance of a power system is thoroughly investigated in (Panda, and Padhy, 2007). The performance of different input signals to the Power Oscillation Damping (POD) controller is also assessed. The transient energy is used as a tool to assess the effectiveness of FACTS devices to damp power system oscillations in (Murali, and Rajaram, 2009). A systematic procedure for modeling, simulation and optimally tuning the parameters of a SSSC controller for power system stability enhancement is presented in (Panda, 2010).

Several optimization techniques have been adopted to solve a variety of engineering problems in the past decade. GA has attracted the attention in the field of controller parameter optimization. Although GA is very satisfactory in finding global or near global optimal result of the problem; it needs a very long run time that may be several minutes or even several hours depending on the size of the system under study. Moreover swarming strategies in bird flocking and fish schooling are used in the PSO and introduced in (Kennedy and Eberhart, 1995). However, PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. Also, the algorithm cannot work out the problems of scattering and optimization (Rini, Shamsuddin, and Yuhaniz, 2011; Selvi, and Umarani, 2010). In addition, the algorithm pains from slow convergence in refined search stage, weak local search ability and algorithm may lead to possible entrapment in local minimum solutions. A relatively newer evolutionary computation algorithm, called BF scheme has been addressed by (Passino, 2002; Mishra, 2005; Fogel, 1995) and further established recently by (Ali and Abd-Elazim, 2011). The BF algorithm depends on random search directions which may lead to delay in reaching the global solution. A new algorithm BF oriented by PSO is developed that combine the above mentioned optimization algorithms (Korani, 2008; Biswas, Dasgupta, Das, and Abraham, 2007; Abd-Elazim, and Ali, 2012). This combination aims to make use of PSO ability to exchange social information and BF ability in finding a new solution by elimination and dispersal. This new hybrid algorithm called Bacterial Swarm Optimization (BSO) is adopted in this paper to solve the above mentioned problems and drawbacks.

This paper proposes a new optimization algorithm known as BSO for optimal designing of the SSSC to damp power system oscillations. The performance of BSO has been compared with these of PSO and BFOA in tuning the SSSC damping controller parameters. The design problem of the proposed controller is formulated as an optimization problem and BSO is employed to search for optimal controller parameters. By minimizing the time domain objective function, in which the deviations in the speed, DC voltage and transmission line power are involved; stability performance of the system is improved. Simulation results assure the effectiveness of the proposed controller in providing good damping characteristic to system oscillations over a wide range of loading conditions. Also, these results validate the superiority of the proposed method in tuning controller compared with BFOA and PSO.

Power System Modelling

SSSC is installed in series with transmission line as shown in Fig. 1. The generator is represented by the third order model that comprising of the electromechanical swing equations and the generator internal voltage equation. The IEEE type ST1 excitation system is used (Kundur, 1994). Details of system data are given in appendix.

$$\dot{\delta} = \omega_B(\omega - 1) \tag{1}$$

$$\dot{\omega} = \frac{1}{\tau_j}\left(P_m - P_e - D(\omega - 1)\right) \tag{2}$$

where P_m and P_e are the input and output powers of the generator, respectively; τ_j and D are the inertia constant and damping coefficient, respectively; δ and ω are the rotor angle and speed, respectively; ω_B is the synchronous speed.

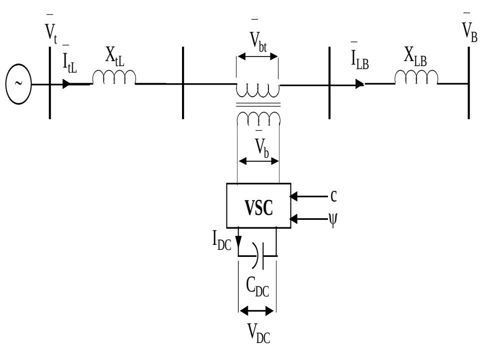

FIG. 1 SMIB WITH SSSC

The output power of the generator can be expressed in terms of the d axis and q axis components of the armature current and terminal voltage as following:

$$P_e = v_d i_d + v_q i_q \tag{3}$$

The internal voltage, E'_q equation is shown below:

$$\dot{E}'_q = \frac{-1}{\tau'_{do}} E'_q + \frac{1}{\tau'_{do}} E_{fd} + \left(\frac{X_d - X'_d}{\tau'_{do}} \right) i_d \tag{4}$$

where E_{fd} is the field voltage; τ'_{do} is the open circuit field time constant; X_d and X'_d are the d axis reactance and d axis transient reactance of the generator, respectively.

Modeling of SMIB with SSSC

The SSSC is a VSC connected in series with the transmission line at its midpoint through an insertion transformer as shown in Fig. 1. The SSSC output voltage is defined by the following equation (Castro, Ayres, Da-Costa, and Da-Silva, 2007; Mandour, and Abd-Elazeem, 2009):

$$\bar{V}_b = cV_{DC}(\cos\psi + j\sin\psi) \tag{5}$$

Where c is the amplitude modulation ratio, ψ is the phase angle modulation ratio of the SSSC and V_{DC} is the SSSC DC voltage.

The transmission line current is described by the following equation:

$$I_{tL} = I_{tLq} + jI_{tLd} \tag{6}$$

The SSSC DC voltage differential equation is given below:

$$\dot{V}_{DC} = \frac{c}{C_{DC}} \{I_{tLq}\cos\psi + I_{tLd}\sin\psi\} \tag{7}$$

The induced AC system voltage due to SSSC voltage is described by the following equation:

$$\bar{V}_{bt} = \bar{V}_b + jX_b \bar{I}_{tL} \tag{8}$$

Substitute from equations (5) and (6) into equation (8), and then divide it into d and q axis as following:

$$V_{btq} + jV_{btd} = cV_{DC}(\cos\psi + j\sin\psi) + jX_b(I_{tLq} + jI_{tLd}) \tag{9}$$

The machine terminal voltage is described as following:

$$\bar{V}_t = j(X_{tL} + X_{LB})\bar{I}_{tL} + \bar{V}_{bt} + \bar{V}_B = V_q + jV_d \tag{10}$$

From equations (6), and (9) the transmission line current in d and q axis are defined as following:

$$I_{tLq} = \frac{1}{(X_{tL} + X_{LB})} \{V_d - V_{btd} - V_B \sin\delta\} \tag{11}$$

$$I_{tLd} = \frac{1}{(X_{tL} + X_{LB})} \{-V_q + V_{btq} + V_B \cos\delta\} \tag{12}$$

AC Voltage Regulator

The AC voltage regulator controls (Bamasak, and Abido, 2005) the reactive power exchange with the power system as shown in Fig. 2.

Where Kp_{ac}, and Ki_{ac} are the PI controller gains for AC voltage regulator, K, and T_1 to T_4 are the lead lag controller gains for additional controller in the AC voltage regulator circuit, U_S is the output signal of additional controller in the AC voltage regulator circuit, and T_W, is the washout time constants for AC voltage regulator and its additional controller respectively.

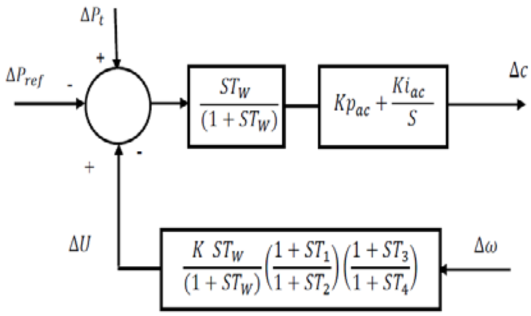

FIG. 2 SSSC DYNAMIC MODEL OF AC VOLTAGE REGULATOR

DC Voltage Regulator

The DC voltage regulator controls (Bamasak, and Abido, 2005) the DC voltage across the DC capacitor of the SSSC controller as shown in Fig. 3.

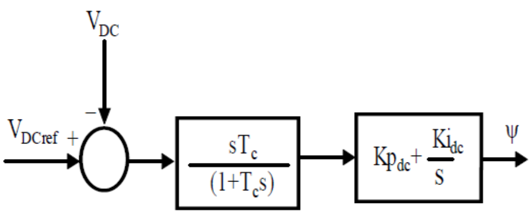

FIG. 3 SSSC DYNAMIC MODEL OF DC VOLTAGE REGULATOR

Where Kp_{dc}, and Ki_{dc} are the PI controller gains for DC voltage regulator, V_{DC} is the SSSC DC voltage,

and T_c is the washout time constant for DC voltage regulator respectively. To reduce the computational burden in this study, the value of the wash out time constants T_c and T_W are fixed to 8 second, the values of T_2 and T_4 are kept constant at a reasonable value of0.05 second. The parameters of the AC, DC, and additional controller are to be determined via various optimization techniques.

Objective Function

In the present study, an integral time absolute error of the speed deviations, DC voltage and transmission line power of SSSC is taken as the objective function expressed as follows:

$$J = \int_0^{t_{sim}} t\left\{|\Delta\omega| + |\Delta V_{DC}| + |\Delta P_t|\right\} dt \tag{13}$$

The great advantage of this objective function is that the effect of SSSC signal is taken into consideration. The problem constraints are the SSSC controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem:

Minimize J (13) Subject to

$$Kp_{dc}^{\min} \le Kp_{dc} \le Kp_{dc}^{\max} \tag{14}$$

$$Ki_{dc}^{\min} \le Ki_{dc} \le Ki_{dc}^{\max} \tag{15}$$

$$Kp_{ac}^{\min} \le Kp_{ac} \le Kp_{ac}^{\max} \tag{16}$$

$$Ki_{ac}^{\min} \le Ki_{ac} \le Ki_{ac}^{\max} \tag{17}$$

$$K^{\min} \le K \le K^{\max} \tag{18}$$

$$T_1^{\min} \le T_1 \le T_1^{\max} \tag{19}$$

$$T_3^{\min} \le T_3 \le T_3^{\max} \tag{20}$$

Hybrid BFOA-PSO Optimization Algorithm

Overview of BFOA

Natural selection tends to eliminate animals with poor foraging strategies and favour the propagation of genes of those animals that have successful foraging strategies since they are more likely to enjoy reproductive success. After many generations, poor foraging strategies are either eliminated or shaped into good ones. The Escherichia coli bacteria that are present in human intestine also undergo a foraging strategy. The control system of these bacteria that dictates how foraging should proceed can be subdivided into four sections namely Chemotaxis, Swarming, Reproduction and Elimination and Dispersal (Mishra, 2005; Fogel, 1995).

Chemotaxis

The characteristics of movement of bacteria in search of food can be defined in two ways, i.e. swimming and tumbling together known as chemotaxis. A bacterium is said to be ‘swimming’ if it moves in a predefined direction, and ‘tumbling’ if moving in an altogether different direction. Mathematically, tumble of any bacterium can be represented by a unit length of random direction $\phi(j)$ multiplied by step length of that bacterium $C(i)$. In case of swimming, this random length is predefined.

Swarming

For the bacteria to reach at the richest food location, it is desired that the optimum bacterium till a point of time in the search period should try to attract other bacteria so that together they converge at the desired location more rapidly. To achieve this, a penalty function based upon the relative distances of each bacterium from the fittest bacterium till that search duration, is added to the original cost function. Finally, when all the bacteria have merged into the solution point, this penalty function becomes zero. The effect of swarming is to make the bacteria congregate into groups and move as concentric patterns with high bacterial density.

Reproduction

The original set of bacteria, after getting evolved through several chemo tactic stages reaches the reproduction stage. Here, best set of bacteria gets divided into two groups. The healthier half replaces with the other half of bacteria, which gets eliminated, owing to their poorer foraging abilities. This makes the population of bacteria constant in the evolution process.

Elimination and Dispersal

In the evolution process, a sudden unforeseen event can occur, which may drastically alter the smooth process of evolution and cause the elimination of the

set of bacteria and/or disperse them to a new environment. Most ironically, instead of disturbing the usual chemotactic growth of the set of bacteria, this unknown event may place a newer set of bacteria nearer to the food location. From a broad perspective, elimination, and dispersal are parts of the population level long distance motile behavior. In its application to optimization, it helps in reducing the behavior of *stagnation* often seen in such parallel search algorithms. The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in (Fogel, 1995; Ali and Abd-Elazim, 2011). Fig. 4.shows the flow chart of BFOA algorithm.

Bacterial Foraging Algorithm

The algorithm of this technique involves two steps.

[Step 1] Initialization

i) p is the number of parameters to be optimized.

ii) S is the number of bacteria to be used for searching the total region.

iii) N_S is the swimming length after which tumbling of bacteria will be undertaken in a chemotactic loop.

iv) N_C is the number of iteration to be undertaken in a chemotactic loop ($N_C > N_S$).

v) N_{re} is the maximum number of reproduction to be undertaken.

vi) N_{ed} is the maximum number of elimination and dispersal events to be imposed over the bacteria.

vii) P_{ed} is the probability with which the elimination and dispersal will continue.

viii) P (1-p, 1-S, 1) is the location of each bacterium which is specified by random numbers on [-1, 1].

ix) The value of C (*i*) which is assumed to be constant in this case for all the bacteria to simplify the design strategy.

x) The values of $d_{attract}$, $\omega_{attract}$, $h_{repelent}$ and $\omega_{repelent}$.

[Step-2] Iterative algorithm for optimization

This section models the bacterial population chemotaxis, swarming, reproduction, elimination and dispersal (initially, j=k=l=0). For the algorithm updating θ^i automatically results in updating of P.

[1] Elimination-dispersal loop: l=l+1

[2] Reproduction loop: k=k+1

[3] Chemotaxis loop: j=j+1

a) For i=1, 2… S, calculate cost function value for each bacterium ias follows.

- Compute value of cost function $J(i,j,k,l)$.

Let $J_{sw}(i,j,k,l) = J(i,j,k,l) + J_{cc}(\theta^i(j,k,l), P(j,k,l))$.

J_{cc} Is defined by the following equation

$$J_{cc}(\theta, P(j,k,l)) = \sum_{i=1}^{S} J_{cc}(\theta, \theta^i(j,k,i))$$

$$= \sum_{i=1}^{S}\left[-d_{attract}\, exp\left(-\omega_{attract}\sum_{m=1}^{p}(\theta_m - \theta_m^i)^2\right)\right]$$

$$+ \sum_{i=1}^{S}\left[h_{repelent}\, exp\left(-\omega_{repelent}\sum_{m=1}^{p}(\theta_m - \theta_m^i)^2\right)\right] \quad (21)$$

- Let $J_{last} = J_{sw}(i,j,k,l)$ to save this value since one may find a better cost via a run.
- End of For loop
- b) For i=1, 2,….S take the tumbling/swimming decision
- Tumble: generate a random vector $\Delta(i) \in \Re^p$ with each element $\Delta_m(i)$ m=1,2,…p,
- Move: Let
$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$$

Fixed step size in the direction of tumble for bacterium i is considered.

Compute $J(i,j+1,k,l)$ and

$$J_{sw}(i,j+1,k,l) = J(i,j+1,k,l) + J_{cc}(\theta^i(j+1,k,l), P(j+1,k,l))$$

Swim

i) Let m=0 (counter for swim length).

ii)While $m < N_S$ (have not climbed down too long)

- Let m=m+1
- If $J_{sw}(i,j+1,k,l) < J_{last}$ (if doing better), let $J_{last} = J_{sw}(i,j+1,k,l)$ and let

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$$

and use this $\theta^i(j+1,k,l)$ to compute the new $J(i,j+1,k,l)$

- Else, let $m = N_S$. This is the end of the while statement.

iii) Go to next bacterium (i+1) if $i \neq S$

[4] If j< N_c, go to [step 3]. In this case, continue chemotaxis, since the life of the bacteria is not over.

[5] Reproduction

a) For the given k and l, and for each i=1,2, ..S, let $J^i_{health} = \min_{j \in \{1...N_c\}} \{J_{sw}(i,j,k,l)\}$ be the health of the bacterium i(a measure of how many nutrients it got over its life time and how successful it was at avoiding noxious substance). Sort bacteria in order of ascending cost J_{health}.

b) The $S_r = S/2$ bacteria with highest J_{health} values die and other S_r bacteria with the best value split.

[6] If k< N_{re}, go to [step 2]. In this case, one has not reached the number of specified reproduction steps, so one starts the next generation in the chemotactic loop.

[7] Elimination-dispersal: for $i = 1,2,....,N$, with probability P_{ed}, eliminate and disperse each bacterium, and this result in keeping the number of bacteria in the population constant. To do these, if you eliminate a bacterium, simply disperse one to a random location on the optimization domain. If l< N_{ed}, then go to [step 2]; otherwise end.

The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in (Passino, 2002; Mishra , 2005; Fogel, 1995).

Overview of PSO

PSO is a stochastic optimization technique that draws inspiration from the behavior of a flock of birds or the collective intelligence of a group of social insects with limited individual capabilities. In PSO a population of particles is initialized with random positions $\vec{X}_i$ and velocities $\vec{V}_i$, and a fitness function using the particle's positional coordinates as input values. Positions and velocities are adjusted, and the function is evaluated with the new coordinates at each time step. The velocity and position update equations for the d-th

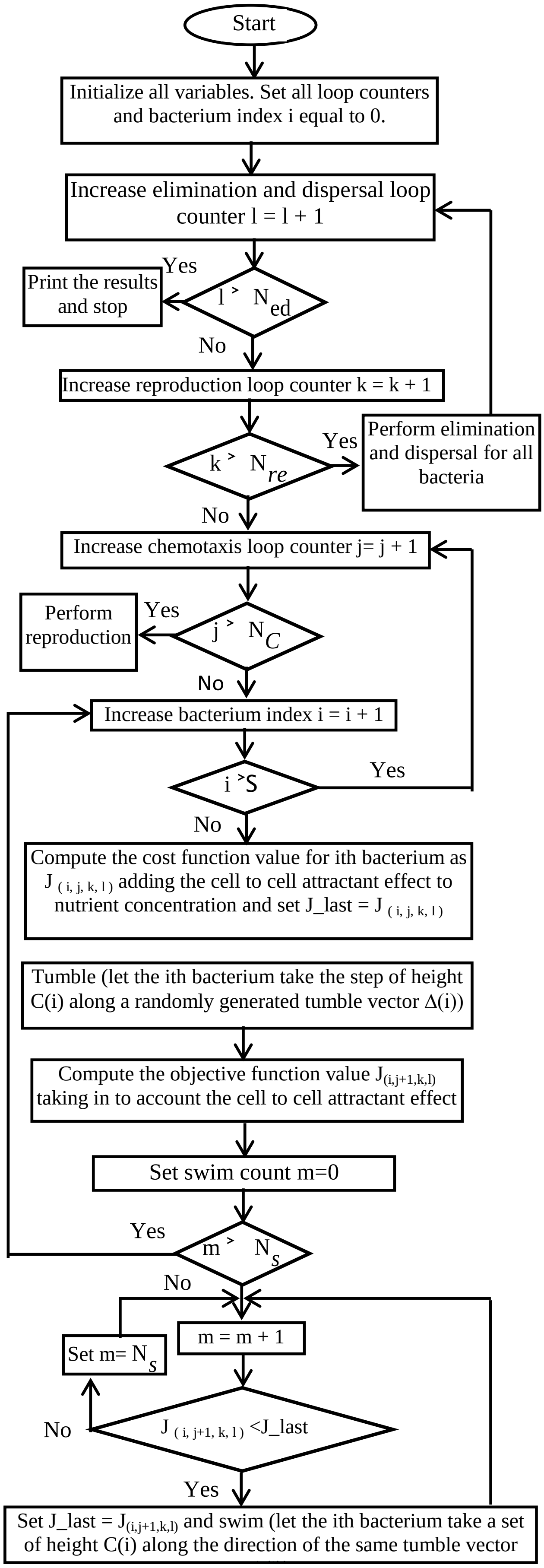

FIG. 4 FLOW CHART OF BFOA

dimension of the i-th particle in the swarm may be given as follows:

$$V_{id}(t+1) = \omega . V_{id}(t) + C_1.\varphi_1.(X_{lid} - X_{id}(t)) + C_2.\varphi_2.(X_{gd} - X_{id}(t)) \quad (22)$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \quad (23)$$

Where

$V_{id}(t+1))$, $V_{id(t)}$: The updated and current particles velocities, respectively.

$X_{id}(t+1))$, $X_{id(t)}$: The updated and current particles positions, respectively.

X_{lid} , X_{gd} : The local and global best position of each particle.

C_1, C_2 : are two positive constants.

φ_1, φ_2 : are unit random numbers within the range [0, 1].

w: is the inertia weight.

Fig. 5.shows the flow chart of PSO algorithm.

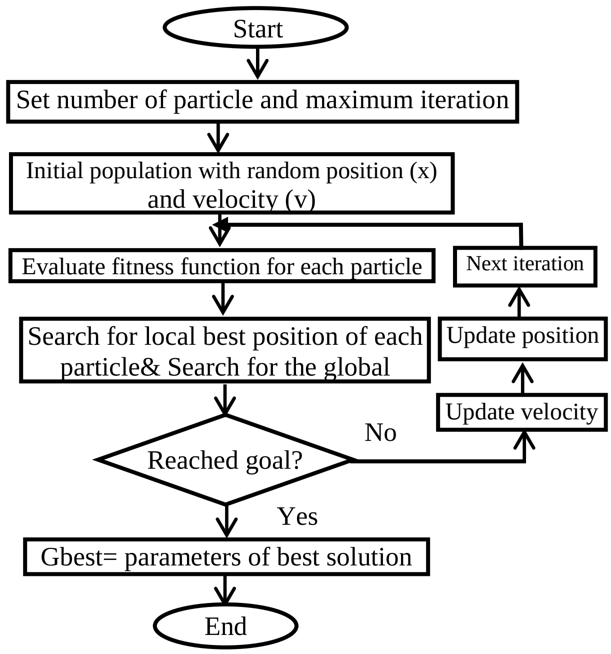

Fig. 5 FLOW CHART OF PSO ALGORITHM

Overview of BSO

BSO combines both algorithms BFOA and PSO thus using advantages of both techniques. The aim is to make use of PSO ability to exchange social information and BFOA ability in finding a new solution by elimination and dispersal. In BFOA, a unit length direction of tumble behavior is randomly generated which may lead to delay in reaching the global solution. In the BSO, technique the unit length random direction of tumble behavior can be obtained by the global best position and the best position of each bacterium by PSO algorithm. The proposed BSO algorithm to search optimal values of parameters is shown in Fig. 6 and described as follows (Korani, 2008; Biswas, Dasgupta, Das, and Abraham, 2007;).

[Step 1] Initialize parameters

$n, S, N_C, N_{re}, N_{ed}, P_{ed}, C(i)(i = 1,2,........., N), \phi^i$.

[Step 2] Update the following

$J(i, j, k)$: Cost or fitness value of the i-th bacterium in the j-thchemotaxis, and the k-th reproduction loop.

$\vec{\theta}_{g\_best}$:Position vector of the best position found by all bacteria.

$J_{best}(i, j, k)$: Fitness value of the best position found so far.

[Step 3] Reproduction loop: $k = k + 1$

[Step 4] Chemotaxis loop: $j = j + 1$

[Sub step a] For i=1, 2,…, S, take a chemotaxis step for bacterium i as follows.

[Sub step b] Compute fitness function, $J(i, j, k)$.

- Let $m = m + 1$
- If $J(i, j+1, k) < J_{last}$ (if doing better),
- Let $J_{last} = J(i, j+1, k)$ and let

  $$\theta(i, j+1, k) = \theta(i, j, k) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$$ and

  use this $\theta(i, j+1, k)$ to compute the new $J(i, j+1, k)$ as shown in new [sub step f]
- Else, let $m = N_S$. This is the end of the while statement.

[Step 5] Mutation with PSO operator

For i=1, 2,……, S

- Update the $\vec{\theta}_{g\_best}$ and $J_{best}(i, j, k)$
- Update the position and velocity of the d-th coordinate of the i-th bacterium according to the following rule:

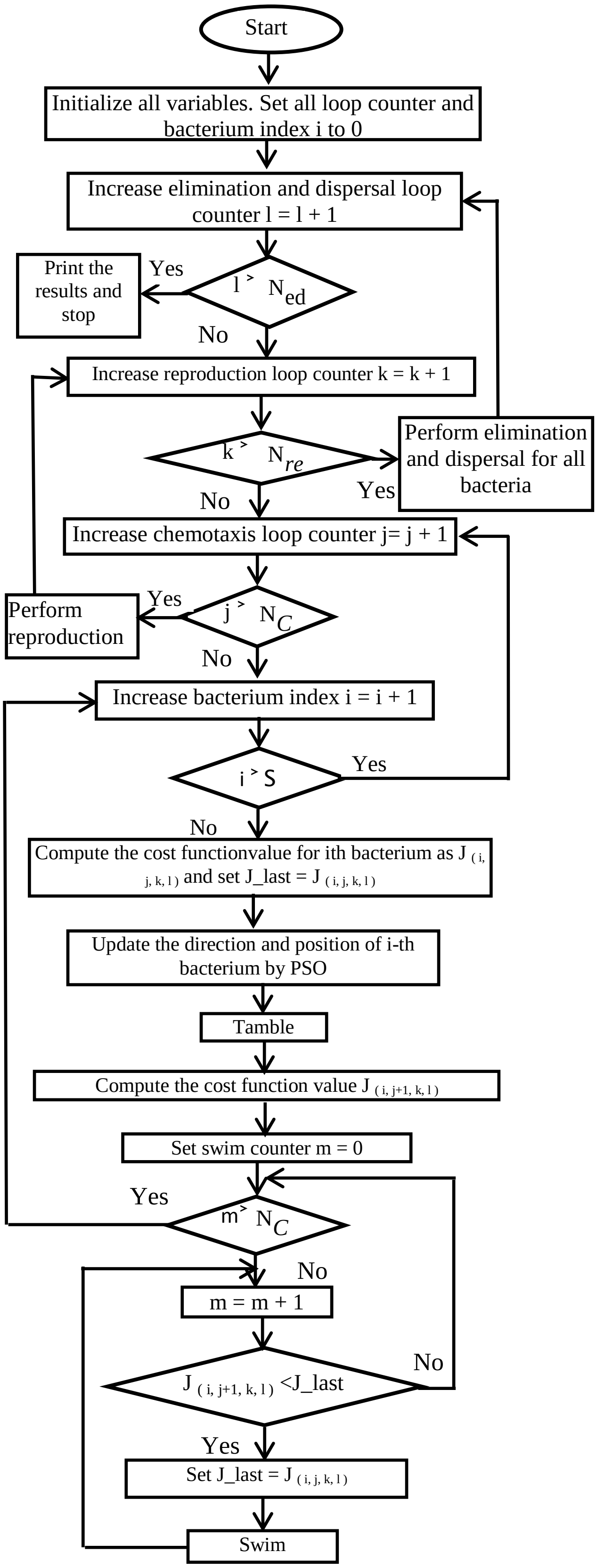

FIG. 6 FLOW CHART OF BSO ALGORITHM

$$V_{id}^{new} = \omega V_{id}^{new} + C_1.\varphi_1.\left(\theta_{g\_best_d} - \theta_d^{old}(i, j+1, k)\right)$$

$$\theta_d^{new}(i, j+1, k) = \theta_d^{old}(i, j+1, k) + V_{id}^{new}$$

[Step 6] Let $S\_r = S/2$

The S_r bacteria with highest cost function (J) values die and other half bacteria population with the best values split.

[Step 7] If $k < N_{re}$, go to [step 1]. One has not reached the number of specified reproduction steps, so one starts the next generation in the chemotaxis loop.

More details of BFOA and PSO parameters are presented in Appendix.

Results and Simulations

In this section, the superiority of the proposed BSO algorithm in designing SSSC (BSOSSSC) in compare to optimized SSSC with PSO (PSOSSSC) and optimized SSSC controller based on BFOA (BFSSSC) is illustrated.

Fig. 7.shows the variations of objective function with different optimization techniques. The algorithm is run keeping limiting value of cost function at 10^{-5}. The objective functions decrease monotonically over generations of BFOA, PSO and BSO. Moreover, BSO converges at a faster rate (43 generations) compared to that for PSO (62 generations) and BFOA (75 generations).

Computational time (CPU) of all algorithms is compared based on the average CPU time taken to converge the solution. The average CPU for BSO is 21.34 second while it is 27.42 and 34.26 second for PSO and BFOA respectively. It is clear that, average convergence time for BSO is less than other methods. The higher computational time forBFOA is expected due to its dependence on random search directions which may lead to delay in reaching the global solution. On the other hand, PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. In addition, the algorithm pains from slow convergence in refined search stage, weak local search ability and algorithm may lead to possible entrapment in local minimum solutions.

Table 1, shows the system eigenvalues, and damping ratio of mechanical mode with three different loading conditions. It is clear that the BSOSSSC shift substantially the electromechanical mode eigenvalues to the left of the S-plane and the values of the damping factors with the proposed BSOSSSC are significantly improved to be (σ =-2.291,-1.8016,-1.11) for light, normal, and heavy loading respectively. Also, the damping ratios corresponding to BSOSSSC controllers are almost greater than those corresponding to PSOSSSC and BFSSSC ones. Hence, compared to BFSSSC and PSOSSSC, BSOSSSC greatly enhances the system stability and improves the damping characteristics of electromechanical modes.

Table 2, shows the controller parameters of DC voltage regulator, AC voltage regulator, and the additional controller obtained by various algorithms.

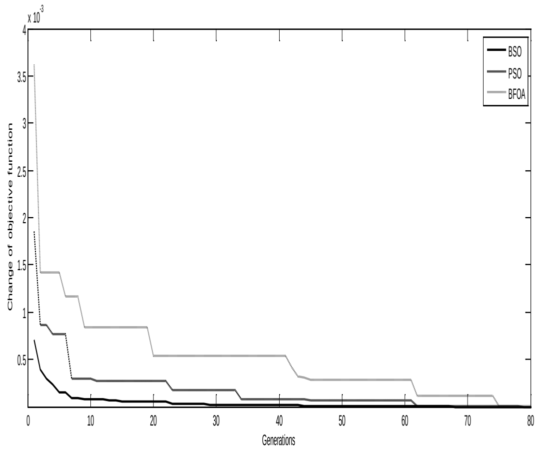

FIG. 7 VARIATIONS OF OBJECTIVE FUNCTION

TABLE 1 MECHANICAL MODES AND DAMPING RATIOS FOR VARIOUS CONTROLLERS AND OPERATING CONDITION

	BFSSSC	PSOSSSC	BSOSSSC
Light load	-1.4487 ± 7.804j (0.183)	-1.778 ± 8.89j (0.196)	-2.291 ± 10.36j (0.216)
Normal load	-1.222 ± 6.1608j (0.195)	-1.474 ± 6.544j (0.22)	-1.8016 ± 6.915j (0.2521)
Heavy load	-0.656 ± 4.95j (0.1314)	-0.785 ± 5.26j (0.148)	-1.11 ± 6.18j (0.1768)

TABLE 2 THE CONTROLLER PARAMETERS FOR VARIOUS CONTROLLERS

	BFSSSC	PSOSSSC	BSOSSSC
Kp_{dc}	0.5398	0.8594	1.8077
Ki_{dc}	1.7412	0.1041	1.814
Kp_{ac}	1.9673	2.5581	3.6947
Ki_{ac}	0.0527	1.2907	0.6113
K	0.0994	0.1432	0.1016
T_1	0.761	0.4984	0.5655
T_3	0.5569	0.3121	0.4937

Response under normal load condition:

The effectiveness of the performance under 0.2 step increase in mechanical torque is applied. Fig. 8 shows the response of speed for normal loading condition. This figure indicates the capability of the BSOSSSC in reducing the settling time and damping power system oscillations. Moreover, the mean settling time of these oscillations is 3.5, 3.8, and 4.2 second for BSOSSSC, PSOSSSC, and BFSSSC respectively. In addition, the proposed BSOSSSC outperforms and outlasts PSOSSSC and BFSSSC controller in damping oscillations effectively and reducing settling time.

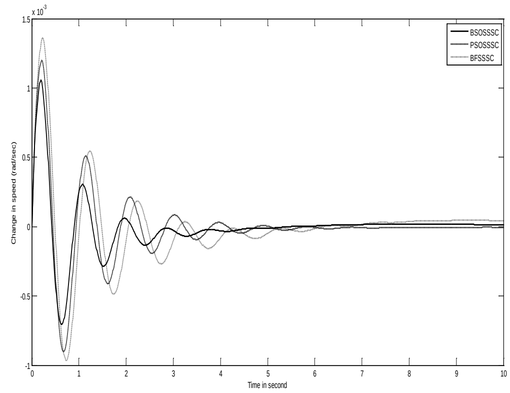

FIG. 8 CHANGE IN SPEED FOR NORMAL LOAD CONDITION

Response under heavy load condition:

Fig. 9 shows the system response at heavy loading condition with fixing the controller parameters. From this figure, it can be seen that the response with the proposed BSOSSSC shows good damping characteristics to low frequency oscillations and the system is more quickly stabilized than PSOSSSC and BFSSSC. The mean settling time of oscillation is 3.2, 3.8, and 4.1 second for BSOSSSC, PSOSSSC, and BFSSSC respectively. Hence, the proposed BSOSSSC extend the power system stability limit.

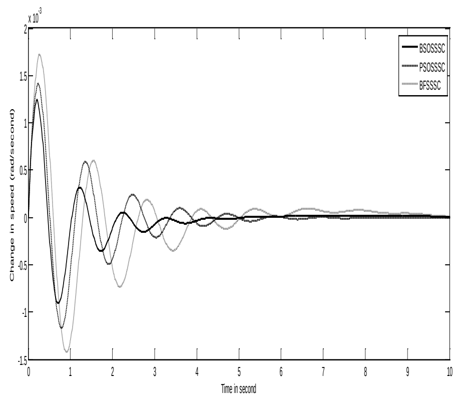

FIG. 9 CHANGE IN SPEED FOR HEAVY LOAD CONDITION

Conclusions

In this study, a new optimization algorithm known as BSO, which synergistically couples the BFOA with the PSO for optimal designing of SSSC damping controller is thoroughly investigated. For the proposed controller design problem, an integral time absolute error of the speed, DC voltage and transmission line power of SSSC is taken as the objective function to improve the system response in terms of the settling time and overshoots. The superiority of this objective function is that the effect of SSSC signal is taken into consideration. Simulation results are presented for various loading conditions to verify the effectiveness of the proposed controller design approach. Moreover, the proposed control scheme is robust, simple to implement, yet is valid over a wide range of operating conditions.

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APPENDIX

The system data are as shown below:

a) Synchronous generator (p.u) X_d =1.07, X_q =1.0, $X_d^{'}$ =0.3, $\tau_{do}^{'}$ =5.9, H=2.37, Pe=0.9, Vt=1.0.

b) Excitation system K_A =400 and T_A =0.05 sec.

c) Transmission line (p.u), X_{tL} =0.3, X_{LB} =0.3

d) SSSC parameters (p.u), X_b =0.05, V_{DC} =1.0, C_{DC} =1.0.

e) Bacteria parameters: Number of bacteria =10; number of chemotatic steps =10; number of elimination and dispersal events = 2; number of reproduction steps = 4; probability of elimination and dispersal = 0.25; the values of $d_{attract}$ =0.01; the values of $\omega_{attract}$ =0.04; the values of $h_{repelent}$ =0.01; the values of $\omega_{repelent}$ =10.

f) PSO parameters: $C_1 = C_2$ =2.0, ω =0.9.